Jets as probes for precision measurement and candles for physics beyond standard model

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Rahul Basu Memorial Thesis Award Seminar
In this talk ...

- Measurement of the dependence of inclusive jet production cross sections on the anti-$k_T$ distance parameter in proton-proton collisions at $\sqrt{s} = 13$ TeV
  SC, G. Majumder [CMS Collaboration]
  CMS-PAS-SMP-19-003, JHEP12(2020)082

- Search for $W'$ boson decaying to a top and a bottom quark
  SC, A. O. M. Iorio, G. Majumder [CMS Collaboration]
  CMS-PAS-B2G-20-005, to be submitted in PLB

- Jets with electrons from boosted top quarks
  SC, R. Godbole, T. S. Roy
  JHEP01(2020)170
Jets

Theory calculation

Parton shower + Hadronization + Decay

Real experiment

Jet algorithm

Group of collimated spray of hadrons created from hadronization of q/g
Jet formation @LHC

Two possible origins

Quark-gluon, quark-quark, gluon-gluon scatterings

Decay of heavy particles

Default jet reconstruction algorithm @LHC: Anti-$k_T$ (circular jet with hard core)

[Cacciari, Salam, Soyez]

Parameter in anti-$k_T$ algorithm:

distance parameter $R$ (~ jet radius)

Find more details on jets in Arun’s talk
Radius scan for inclusive jets

Dependence of inclusive jet production on the anti-k_{T} distance parameter in pp collisions at \( \sqrt{s} = 13 \text{ TeV} \)

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: The dependence of inclusive jet production in proton-proton collisions with a center-of-mass energy of 13 TeV on the distance parameter \( R \) of the anti-\( k_{T} \) algorithm is studied using data corresponding to integrated luminosities up to 35.9 fb\(^{-1}\) collected by the CMS experiment in 2016. The ratios of the inclusive cross sections as functions of transverse momentum \( p_{T} \) and rapidity \( y \), for \( R \) in the range 0.1 to 1.2 to those using \( R = 0.4 \) are presented in the region \( 84 < p_{T} < 1588 \text{ GeV} \) and \( |y| < 2.0 \). The results are compared to calculations at leading and next-to-leading order in the strong coupling constant using different parton shower models. The variation of the ratio of cross sections with \( R \) is well described by calculations including a parton shower model, but not by a leading-order quantum chromodynamics calculation including nonperturbative effects. The agreement between the data and the theoretical predictions for the ratio of cross sections is significantly improved when next-to-leading order calculations with nonperturbative effects are used.

Keywords: Hadron-Hadron scattering (experiments), Jets, QCD

ArXiv ePrint: 2005.05150
Jet formation @LHC

Hard Scattering

Parton branching

Hadronization

Underlying event

Energy loss from parton → jet

$\delta p_T \sim - C p_T \ln(R)$

$\delta p_T \sim - C / R$

$\delta p_T \sim R^2$

Modeling in simulation

All purpose event generators
(PYTHIA, HERWIG, SHERPA, ..)

Generators of hard interaction
(MADGRAPH, POWEG)
Matrix element calculators
(NLOJet++)

@LO (PYTHIA, HERWIG++, MADGRAPH)
@NLO (POWHEG, HERWIG7)
in pQCD

$p_T$ ordered
(PYTHIA) / angle ordered
(HERWIG)

Emperical models:
Lund string (PYTHIA),
color cluster (HERWIG)

Multiparton interaction
with tunable parameters
(PYTHIA & HERWIG)

hep-ph : 0712.3014

CMS-SMP-19-003
Comparison of ratio of cross sections

Observable: Ratio of differential cross sections w. r. t. AK4 jets

Comparison: Data to Powheg+Pythia8 (NLO+PS) prediction

\[
\frac{d^2\sigma}{dp_Tdy} (AK_n) [n=1-12]
\]

\[
\frac{d^2\sigma}{dp_Tdy} (AK4)
\]

Jet size \( R = 0.1 \times n \)

Good data-simulation agreement for small and medium jet sizes

Need better modeling of underlying event in Pythia8 for large radii
Comparison of ratio of cross sections

**Observable:** Ratio of differential cross sections w. r. t. AK4 jets

**Comparison:** Data to fixed order pQCD calculations

- LO $\rightarrow$ NLO $\Rightarrow$ significant improvement in description
- Nonperturbative correction (for hadronization+UE) $\Rightarrow$ essential to describe data
- Good description by resummed calculations

NLO+NLL predictions provided by S. Moch et al
Comparison of cross section vs $R$

Observable: Inclusive jet cross sections in a in $p_T$ and rapidity range
(divided by Herwig7 prediction for AK4 jets)

Comparison: pQCD calculations & parton shower MC predictions

- Different trends in fixed order prediction and MC simulations
- PYTHIA8 and HERWIG++ (LO predictions) at two boundaries
- NLO predictions from simulations within envelope
**Comparison of cross section vs R**

**Observable**: Inclusive jet cross sections in a in $p_T$ and $y$ range

(divided by corresponding prediction/data for AK4 jets)

**Comparison**: Data to fixed order pQCD calculations & parton shower MC predictions

- Different trend in fixed order prediction @ LO w. r. t. data
- Much improvement in with prediction NLO calculations
- Nice description of data by resummed fixed order calculations

Very fast measurement of its kind!

Low $p_T$ region complemented by ALICE results
Search for $W' \rightarrow t b$
in hadronic final state

CMS Physics Analysis Summary

Search for a $W'$ boson decaying to a top and a bottom quark at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is performed for a $W'$ boson decaying to a top and a bottom quark in proton-proton collisions at a center-of-mass energy of 13 TeV. The analyzed data have been collected by the CMS Collaboration between 2016 and 2018 and correspond to an integrated luminosity of 137 fb$^{-1}$. Deep neural network algorithms are used to identify the jets initiated by the $b$ quark and also the jets containing the decay products of the top quark when the $W$ boson from the top quark decays hadronically. No excess above the estimated standard model background is observed and upper limits on the production cross section of $W'$ bosons are set. Both left- and right-handed $W'$ bosons with masses below 3.4 TeV are excluded at 95% confidence level. These results are the best limits to date on $W'$ bosons decaying to a top and a bottom quark in the all-hadronic final state.

To be submitted in PLB
Search for $W' \rightarrow t \ b$ in hadronic final state

- $W'$ : A color singlet heavy gauge boson with charge $\pm 1$ spin 1

- Why $W' \rightarrow t \ b$?
  
  Coupling to third generation preferred in a few models
  
  QCD multijet background can be greatly reduced compared to light quark final states
  
  Challenging for $b$ and top tagging at energy frontier

- Strongest limits from collider:
  
  6.0 TeV from ATLAS ($W' \rightarrow e \nu$)
  
  Can be bypassed in leptophobic models, $\nu_R$ heavier than $W'_R$
  
  Enhanced sensitivity for $W' \rightarrow t \ b$

Muller, Nandi 1996
Abdullah et al. 2018
Analysis strategy

- Signature of a heavy $W'(\rightarrow t\ b)$ in detector: a top jet & a b jet with high $p_T$

- **B tagging for AK4 jet (b):**
  deep neural network (DNN) based b quark tagger [CMS-DP-18-033]

- **Top tagging for AK8 jet (t):**
  (soft drop) mass and deep neural network (DNN) based top quark tagger [CMS-DP-17-049]

- Hunt for a bump in $m_{tb}$ spectrum over a smoothly falling non-resonant background
Comparison of data & backgrounds (2017)

Signal region (SR):
Region with maximum signal sensitivity (top-tagged AK8 jet + b-tagged AK4 jet)

![Signal Region Graph]

Validation region (VR):
Where multijet bkg estimation is checked (anti-top-tagged AK8 jet + b-tagged AK4 jet)

![Validation Region Graph]

✔ No significant excess observed in data :(

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**Multijet**

- Estimated from data
- Taken from simulation
- But with a data-based Correction

**Single top**

- Purely from simulation

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41.5 fb⁻¹ (13 TeV)
Results

- Limits on signal yield computed using asymptotic CLs method [Cowan, Crammer, Gross, Vitells]
- Results from three years are combined

Exclusion limits (@ 95% CL): Right-handed $W'$ of mass below $\sim 3.4$ TeV assuming SM-like couplings (3.7 TeV expected)
Tagging boosted tops
decaying into electrons

Jets with electrons from boosted top quarks

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Tagging boosted tops decaying into electrons

Why?

- Interesting new physics signatures in boosted top quarks (just saw it!)
- Get rid of combinatorial problem in top quark reconstruction using large sized jets

Challenges?

- Identification of energetic electron from boosted top quark can be hampered due to close-by hadronic environment
- Complete reconstruction is not possible due to invisible neutrinos
Tagging against SM background (1)

- Start with a high $p_T$ fat (AK8) jet + soft-drop grooming
- Construct observables ($V_e$) using jet constituents
- Check if the jet is consistent with energetic electron buried in hadrons

![Graphs showing neutral fraction of non-hadronic energy and soft-drop mass.](image)

Asymmetry between hadron energy fraction of two subjets

- Some other variables in $V_e$

- One variable in $V_e$
Tagging against SM background (2)

- Start with a high $p_T$ fat (AK8) jet + soft-drop grooming
- Construct observables ($V_e$) using jet constituents
- Check if the jet is consistent with energetic electron buried in hadrons

Train a BDT with
- electronic top jets
  as signal
- &
- b jets
  as bkg

- ✔ Good discrimination against SM backgrounds
- ☹️ Stop quark looks similar to top quark
  (similar visible products in both cases)
Tagging against BSM background

- **Use a hypothesis:** Only invisible particle is neutrino
- **Prescribe a method** to identify electron in the EM-enriched subjet using tracks in it \( \Rightarrow p_e \)
- **Measure b-momentum** from the rest of the jet \( \Rightarrow p_b = p_J - p_e \)
- **Use an ansatz:**
  A massless 4-momentum, \( p_\nu \), collimated to the electron, is added to the electron & (electron + b) system \( \Rightarrow p_e + p_\nu \rightarrow p_W \& p_W + p_b \rightarrow p_t \)
- **Develop variables** \( (V_\nu) \) from \( p_\nu, p_e, p_b \)

\[
\begin{align*}
\frac{E_b}{E_\nu + E_e} \\
1 - \cos \theta_{\nu b} & \quad \& \quad \frac{1 - \cos \theta_{\nu e}}{1 - \cos \theta_{\nu e}}
\end{align*}
\]

Train a BDT with electronic top jets as signal & b jets as bkg

\( \checkmark \) Good separation between stop & top jets

JHEP 01 (2020) 170
Top tagger as anomaly finder

Check population in 2-d plane of BDT responses

\[ t(e) \text{ zone: top enriched} \]

QCD enriched zones

JHEP 01 (2020) 170
Top tagger as anomaly finder

Check population in 2-d plane of BDT responses

Electronic top tagger can also work as an anomaly finder for jets with a hard electron overlapping with hadron shower but not from top decay.
- Dependence of the ratio of inclusive jet cross sections on the distance parameter of anti-$k_T$ algorithm is measured

- Searched for $W' \rightarrow t \ b$ in hadronic final state using the latest development in heavy quark tagging involving deep neural network in CMS and excluded $W'$ bosons with SM-like couplings of mass below $\sim 3.4$ TeV

- New methodology is proposed for identifying boosted top quarks which decay into electrons
Show must will go on!
Backup
Jets: How?

- Sequential recombination

Define a measure of distance between each pair of particles and for each individual particle.

If $d_{ij}$ is smallest among all of them, combine $i$ & $j$ ($p_k = p_i + p_j$).

If $d_{iB}$ is smallest among all of them, declare $i$ as a jet.

Snowmass accord:

Jet algorithms should be infrared and collinear safe.

\[
d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}
\]

\[
d_{iB} = k_{ti}^{2p}
\]

$p = 1 \Rightarrow k_T$

$p = 0 \Rightarrow \text{Cambridge Aachen}$

$p = -1 \Rightarrow \text{anti-k}_T$

- Inverts parton shower
- Based on angular separation
- Hard-to-soft clustering

Most commonly used at LHC

Cacciari, Salam, Soyez
JHEP 0804:063, 2008
Superiority of anti-kT algorithm over others

Stable jet area (both at parton & hadron level)

Jet area is almost independent of $p_T$

Minimum (and smooth) impact of soft particles (UE, pileup) on jet clustering
Object reconstruction in CMS

Particle-flow algorithm
Combines information from different subdetectors in an optimal way
Reconstructs a mutually exclusive list of particles (muon, electron, photon, charged and neutral hadrons)
Used to build higher level objects and variables: jets, missing transverse energy (MET), HT, ..

Significant improvement compared to traditional approaches
(for example, in jet energy resolution, hadronic $\tau$ reconstruction)
Optimal jet size in CMS

Radiation loss increases in Run-2, so the optimum cone size

https://twiki.cern.ch/twiki/bin/view/CMSPublic/MultipleConeSizes14
Trigger efficiency curves

Anti-\(k_T\) CHS R=0.8

![Graph for Turn On \(P_T = 254\) GeV and HLT_AK8PFJet200](#)

![Graph for Turn On \(P_T = 580\) GeV and HLT_AK8PFJet500](#)
MC generators

PYTHIA8
LO generator (2->2)
P_T ordered dipole shower
Lund string model
for hadronization

HERWIG++
LO generator (2->2)
Angle ordered parton shower
Color cluster model
for hadronization

MADGRAPH:
LO generator
(up to 4 partons in final state)

POWHEG:
NLO generator
(dijet + extra radiation to have
the correct NLO prediction)

HERWIG7:
NLO generator

Lund string model

Color cluster model
Cross section ratio & 3-jet production

\[ \sigma(p_T, R) = \alpha_s^2 \sigma^{(2,0)}(p_T) + \alpha_s^3 \left( \sigma^{(3,0)}(p_T, R) + \sigma^{(3,1)}(p_T) \right) + \alpha_s^4 \left( \sigma^{(4,0)}(p_T, R) + \sigma^{(4,1)}(p_T, R) + \sigma^{(4,2)}(p_T) \right) \]

\[ \sigma(p_T, R_1) - \sigma(p_T, R_2) = \alpha_s^3 \left( \sigma^{(3,0)}(p_T, R_1) - \sigma^{(3,0)}(p_T, R_2) \right) + \alpha_s^4 \left( \left( \sigma^{(4,0)}(p_T, R_1) - \sigma^{(4,0)}(p_T, R_2) \right) + \left( \sigma^{(4,1)}(p_T, R_1) - \sigma^{(4,1)}(p_T, R_2) \right) \right) \]

\[ R = \frac{\sigma(p_T, R_1)}{\sigma(p_T, R_2)} = 1 + \alpha_s \frac{\Delta \sigma^{(3,0)}(p_T, R_1, R_2)}{\sigma^2(p_T)} + \alpha_s^2 \frac{\Delta \sigma^{(4,0)}(p_T, R_1, R_2)}{\sigma^2(p_T)} + \frac{\Delta \sigma^{(4,1)}(p_T, R_1, R_2)}{\sigma^2(p_T)} \]

If dijet production cross section at NLO is used in ratio, one misses the first part of \( \alpha_s^2 \) terms.

For dijet production, one needs NNLO calculation to obtain the ratio at \( \alpha_s^2 \) (possible now, but too much time consuming!)

Solution: compute the difference from 3 jet production cross section at NLO (avoids computing 2-loop terms)
Dependence of cross section ratio on $\sqrt{s}$

- Larger values of $\sqrt{s} \Rightarrow$
  Larger gluon fraction in proton

- Gluon jets radiate more than quark jets
  $\Rightarrow$ AK5 suffers more than AK7
Nonperturbative correction for fixed order prediction

- Fixed order calculation provides differential cross section for parton level jets but jets in data are made from hadrons => needs additional correction

- Based on the modelling of hadronization & MPI in simulation

- \( C_{NP} = f(\text{Hadronization & MPI switched on}) / f(\text{Hadronization & MPI switched off}) \)

- Hadronization correction is larger more small jet sizes & MPI correction has significant size for large jet radii

- Correction = average from (Powheg+Pythia8) & (Powheg+Herwig++)
  (difference of Powheg+Pythia8 & Powheg+Herwig++)/2

Uncertainty = (difference of Powheg+Pythia8 & Powheg+Herwig++)/2
Top tagging efficiencies

CMS

Simulation

Top quark vs. QCD multijet

1000 < p_{T}^{\text{gen}} < 1500 \text{ GeV}, |\eta|^{\text{gen}} < 2.4
105 < m_{SD}^{\text{AK8}} < 210 \text{ GeV}
110 < m_{SD}^{\text{CA15}} < 210 \text{ GeV}
140 < m_{\text{HOTVR}} < 220 \text{ GeV}

Background efficiency vs. Signal efficiency

(13 \text{ TeV})

JME-18-002
For large masses of $W'$, single top contribution dominates the LH sample
Thus although real $W'$ signal becomes smaller, total cross section flattens out
**Backgrounds**

**Multijet production in QCD**

Production of top quark pairs with hadronic final state followed by hadronic decay of top quark

Production of single top quark events with hadronic final state

Estimated from data

Estimated from simulation with a data-based correction

Purely from simulation

Small contribution

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CMS-B2G-20-005
Top tagging performance

300<p_T<500 GeV

500<p_T<700 GeV

700<p_T<1000 GeV

p_T>1000 GeV
Validation of multijet background estimation in data

Systematic uncertainty on multijet bkg

Total unc in multijet bkg is within 10%

Systematic uncertainty on $t\bar{t} +$ single top bkg

Uncertainty on b tagging SF, top $p_T$ reweighting are dominant sources of unc for $t\bar{t} +$ single top bkg
Soft drop

1. Undo last stage of CA clustering tree and label two subjets $j_1, j_2$ of jet $j$.
2. If
   \[ z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R_0} \right)^\beta \]
   then $j$ is the soft-dropped jet.
3. Otherwise define $j$ to be the harder subjet and iterate.
   - For $\beta = 0$, drops soft radiation entirely.
   - Provides handle on UE and PU, identifying hard substructure.

QCD, perturbative radiation:
\[ P(z) \sim \frac{1}{2z} \left( 1 + (1-z)^2 \right) \]

Z/W/H/t decay:
\[ P(z) \sim 1 \]

Put an upper cut on $z$ to remove high mass QCD
Search for $t\bar{t}$ resonance in CMS

**Dileptonic**

Compare the signal selection efficiencies!

ATLAS doesn’t even have the dileptonic analysis (public)
Search for $t\bar{t}$ resonance in CMS

Semileptonic

Compare the signal selection efficiencies!
Tagging boosted tops decaying to electrons

• Boosted tops
  new physics with a decaying to top
  combinatorial problem, quarks

• Tagging boosted top quark in

  Hadronic decay

    Pros:
    All the decay products are visible
    => allows complete reconstruction

    A plethora of techniques exists from jet substructure analysis to machine learning algorithms

    Cons: Large multijet background

  Leptonic decay

    Problem:
    Neutrinos carry away variable amount of energy
    => full reconstruction is not possible
    Leptons are not isolated (prone to fakes)

    Advantage for muon:
    Well reconstructed track + mini-isolation
    [Rehermann and Tweedie (hep-ph : 1007.2221)]

    Difficulty for electron:
    Electron identification gets hampered when showers of b and e overlap

  Hint for heavy particle
  Help in SM to reduce specially for events with multiple top

Motivation at 50
Tagging procedure (1) : Samples

- Jets are constructed from particle-flow candidates using anti-$k_T$ algorithm with $R = 0.8$ (AK8)

- Only the leading jet in the event with $p_T > 500$ GeV & $|y| < 2.4$ is used

- Jets are groomed using Soft Drop algorithm
  hard structure and remove soft radiation within jet from underlying event

=> always results to two subjets in the jet (or keeps only one particle)
Tagging procedure (1) : Variables in $V_e$

- Asymmetry between hadron energy fraction of two subjets
  \[ A_h(J) = \frac{(f_h^1 - f_h^2)^2}{(f_h^1 + f_h^2)^2} \]

- For top(e) jets, electron resides in one subjet and products of b quark are contained in the other subjet => large $A_h$

- For hadronic jets, energy deposit in ECAL occurs mostly by photons => not the case for top(e) jets

\[ f_{h_i}^i : \frac{E_{HCAL}^i}{E^i} \text{ for i-th subjet} \]

\[ f_{1-h}^N(J) = \frac{E_\gamma}{E_{\text{non-had}}} = \frac{E_\gamma}{(E_e + E_\mu + E_\gamma)} \]

Other variables (52) (from $\pi^0$ decay)
Tagging procedure (1): Variables in $V_e$

$$r_C = \frac{1}{d_0} \sum_{k \in \text{tracks}} q^{(k)} p_T^{(k)} \Delta R_{k,J}, \quad \text{where} \quad d_0 = \sum_k p_T^{(k)}$$
Tagging procedure (1) : Variables in $V_e$

\[
\tau_N \equiv \frac{1}{R d_0} \sum_k p_T^{(k)} \min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k})
\]

\[
f_{1-h} = 1 - \frac{E_{HCAL}^J}{E_J}
\]
Tagging procedure (1) : Performance

![Graph showing signal and background efficiency](image-url)
Tagging procedure (2) : electron identification

- Take soft drop subjets of AK8 jet (J)
- The subjet (j) with lower hadron energy fraction is likely to contain the electron
- Hardest track in j => T
- Constituents of j are reclustered with $k_T$ algorithm => output : jet $j'$ (with constituents of j with $k_T$ clustering history)
- Take two exclusive $k_T$ subjets of $j'$ => The subjet ($kT1$) which contains T is taken as the electron candidate (e)

- $p_e = p_{kT1}$
- $p_b = p_J - p_e$
Tagging procedure (3)

- **Use an ansatz**: A massless 4-momentum, collimated to the electron, is added to the electron & (electron + b) system

\[ p_\nu = E_\nu \left(1, \frac{\vec{p}_\nu}{E_\nu}\right), \quad \text{with} \quad \vec{p}_\nu = p_\parallel \hat{e} + \vec{p}_\perp \quad \text{where} \quad \hat{e} \cdot \vec{p}_\perp = 0 \]

- **Use kinematic constraints of W mass on the former & top mass on the later**

\[ m_W^2 = (p_e + p_\nu)^2 \quad \quad m_t^2 = (p_b + p_e + p_\nu)^2 \]

Using

\[ r = \frac{|\vec{p}_\perp|}{p_\parallel} = \frac{p_\perp}{p_\parallel} \ll 1 \]

One can show

\[ E_\nu \simeq \frac{1}{2} \frac{m_t^2 - \Delta^2}{m_W^2} \quad \text{where} \quad \Delta^2 = (m_W^2 + m_b^2 + 2p_b \cdot p_e) \]

Construct two variables:

\[ Z_b = \frac{E_b}{E_e + E_\nu} \quad \quad \Theta_{b/e} = \frac{E_e \left(m_t^2 - \Delta^2\right)}{E_b m_W^2} \]

In the limit of high boost ignoring the masses of e and b

\[ \frac{E_b}{E_W} \quad \frac{1 - \cos \theta_{\nu b}}{1 - \cos \theta_{\nu e}} \]

(ignoring the masses of e and b)
Performance

- $r_e$: response of BDT with variables $V_e$ of BDT with variables $V_v$

In process of implementing this algorithm for CMS analysis

Real benefit of $r_v$ carrying tale tell signatures of top decay!

1D responses (s:56)

1D ROC
Multivariate analysis

- Multivariate analysis is performed by constructing two boosted decision trees (BDT)

- BDT_e: input variables V_e, response: r_e
- variables V_ν, response: r_ν

Training: BDT_ν: input
- Signal: t(e) jets
- Background: b jets

P_T reweighing is performed to make the shape of the p_T spectrum of all the samples identical
=> BDT performance is independent of jet p_T

Response r_e separates t(e) jets from b jets, and other hadronic bkg's, but fails to distinguish from stop jets

Real benefit of r_ν carrying
tale tell signatures of top decay!
Tagging procedure (3) : Variables in $V_{\nu}$

- $t(e)$
- $b$
- $t(h)$
- $j$
- $\tilde{t}(e)$

$Z_b$

$\Theta_{b/e}$
Correlation matrices